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Jeff Sawchuk holds a Bachelor of Science in Mechanical Engineering and has been with BP for 22 years. He is currently the LNG Technology Manager within BP’s Upstream Technology Group. He has been involved in a variety of roles in BP’s Gas Processing and LNG operations including; Plant Engineer within BP’s NGL Business Unit in Canada; Lead Process Engineer on several major gas processing projects in North America, Europe, and the Middle East; Engineering Manager on various LNG and NGL development projects in North America and the Middle East; Lead Process Engineering Consultant for major onshore and offshore projects. Jeff is the Technology Sponsor for the Big Green Train – Next Generation Technology Project currently underway.

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Pat Ward has ten years experience with BP and has been involved mainly in the Canadian operations in the areas of sour crude oil production, sour gas production and currently LNG Liquefaction plant design. Previous positions have included plant operator, site engineer, HSE team leader, process engineer and project engineer. For the past year, Pat has served as BP’s Lead Process Engineer on the Big Green Train Project.
BP’s Big Green Train – Next Generation LNG

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BP’s expanding gas resources and its’ goal to be the lowest cost LNG supplier in target markets have created the need for BP to progress the development of “Next Generation” LNG technology.

BP’s Big Green Train Project (BGT) adopts an open approach to technologies, some new to LNG, and sets aggressive metrics for LNG plant design in terms of scale, capital cost per tonne of LNG, life cycle economics and environmental improvements. The LNG plant life cycle cost target is 25% lower than that achieved for Atlantic LNG Train 1 in Trinidad (greenfield basis). Consistent with BP’s environmental expectations, the greenhouse gas emission target was aimed at reducing CO2 emissions by 50%. In addressing these targets, BP has identified and evaluated technology improvements which will be applied in future LNG projects, and have the capability to set new benchmarks in the industry.

LNG plant capacity has increased over time, as illustrated in the chart on the right, driven by economies-of-scale leading to reduced capital costs per tonne of LNG. BP is of the opinion, confirmed through the BGT project, that LNG plant train size will continue to be stretched to maximize these scale advantages, and that future plant sizes will be determined by commercial factors rather than technical limits.

The following topics, which will be discussed in this paper, represent a selection of the key areas identified for study in the BGT Project for the development of Next Generation LNG Technology.

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**Project Metrics**

- Develop Next Generation LNG Plant Options that are Big, Green and Low Cost, and ...
  - Produce 5+ MTPA of LNG
  - Reduce the EPC cost per annual tonne of LNG produced by 25% (as compared to ALNG Train #1)
  - Reduce CO2 emissions per ton of LNG produced by 50% (as compared to ALNG Train #1)

**LNG Plant Capacity vs Start-up Year**

- LNG Plant Capacity vs Start-up Year
LIQUEFIN™ LNG technology developed by Axens/IFP, in collaboration with BP, has been used as the basis for the BGT LNG plant designs. This process uses dual mixed refrigerant (MR) loops for improved flexibility and chiller performance, balanced compression horsepower between the two loops to accommodate common drivers, and aluminum plate fin heat exchangers for the main exchanger service. Consequently, improved process and economic efficiencies can be achieved. Nevertheless, many of the principles described in this paper can be applied to other liquefaction technologies to give improved environmental performance, process efficiency and costs.

**Next Generation LNG Plant Designs**

The BGT study evaluated a range of plant designs that produced between four (4) and nine (9) million tonnes of LNG per annum, and a range of NGL recovery percentages. After evaluating all of the cases with a life-cycle economic model and performing a technical risk session around the refrigeration compressors and drivers, the following three LNG plant design cases were selected for further evaluation:

- Green Frame 7
- Ultimate Aero
- All Electric (eLNG)

These plant designs provide a range of LNG plant capacities, elements of modular expandability, and the potential for step change in energy efficiency, greenhouse gas emissions, life cycle cost and supply flexibility to meet LNG market requirements. A discussion of each design is provided in the following sections.

**Green Frame 7**

The Green Frame 7 Case utilizes two (2) Frame 7E gas turbines to drive the refrigeration compressors on two mixed refrigerant cryogenic loops. Waste heat is recovered from the gas turbine exhausts to increase the efficiency of the plant, reduce the CO₂ emissions and to generate additional low-cost electric power. The electric power is placed on the LNG plant grid to supplement the electric power supplied by LM6000 power generation sets for the large helper motors, inlet gas compression, end-flash compressor, boil-off gas compressor and the balance of the plant. The Green Frame 7 plant design was able to meet the emissions metrics, but fell slightly short of the target for capital cost per annual ton of LNG production ($/tpa).
Ultimate Aero

In the Ultimate Aero design, four (4) LM6000 gas turbine drivers are used to drive parallel refrigeration compressors on the two mixed refrigerant loops. All of the LM6000 gas turbines are equipped with independent refrigeration to cool the inlet air to 7.2°C to generate additional power for the compressors. The inlet air chilling process utilizes an independent Freon refrigeration package as shown in the sketch on the right. The Ultimate Aero provides good elements of modularity for adapting to LNG market requirements. Although a base case design fell short of the aggressive BGT metrics, it is believed to have the potential to meet these targets with additional optimization.

All Electric (eLNG)

Historically, LNG plants have utilized gas turbines and/or steam turbines to drive the refrigeration compressors. The size of the refrigeration compressors has been dictated by the power output of the gas turbines whose power fluctuated with changes in the ambient conditions on a day-to-night and season-to-season basis. This meant that the compressor manufacturer was always challenged to create a design that worked across a range of power inputs rather than optimizing the compressor design to provide constant flow or LNG production. Because electric motors are not manufactured in discrete sizes, this paradigm can be changed. Utilizing electric motors to drive the refrigeration compressors provides an opportunity for the plant owners and the compressor manufacturer to achieve not only improved plant efficiency, but also increased LNG production.

Leveling of LNG production with electric motors relieves the plant operators of their challenge to maintain constant LNG production rates in spite of constantly changing conditions. Downtime due to gas turbine maintenance schedules can also be removed from the availability equation through the use of electric motors, which require less maintenance, have long intervals between maintenance events, and therefore require fewer maintenance personnel. A further advantage is that refrigeration compressors driven by electric motors can be restarted without depressurizing the machine, offering faster restart following maintenance or a trip.

The power supplied by a simple-cycle or combined-cycle power plant to the electric motor-driver is inherently more reliable than the power supplied by a direct gas turbine-driver to the refrigeration compressor. The higher reliability is simply derived from the fact that spare gas turbine-generator set(s) are provided in the power generation facility or back-up power is available from the local electrical grid.
Electric motors have long been utilized to drive a variety of mechanical devices from small fans to large gas compressors. The size of electric motors has been steadily increasing, and the interest shown by LNG ventures is pushing the size of motors to even higher levels as illustrated by the chart to the right.

The design and manufacture of electric motors and frequency converters with power ratings up to 100 MW is now thought to be within the experience level of the major motor manufacturers. As a result, the motor suppliers have expressed their willingness to offer performance guarantees for the electric drive systems envisioned by the LNG industry. Their experience with large generators in power generation service provides much of this comfort. Other electrical system components required for operating the electric drive plant have numerous references to demonstrate their mature design and operating reliability.

The eLNG plant design uses four large electric motors equipped with variable frequency drives (VFDs) to drive four parallel refrigeration compressors. A combined-cycle electric power plant based on large industrial gas turbines provides a dedicated power supply. The overall plant efficiency for eLNG, including the power plant, is higher than both the Green Frame 7 and the Ultimate Aero. The eLNG plant design exceeded all of the project metric targets in terms of capital cost per annual tonne of LNG production, in CO₂ emissions per tonne of LNG and in operating cost.

BP believes the eLNG plant has the potential to set the next benchmarks for the LNG industry.

**Technical Limits**

The BGT Project Team reviewed the technical limitations associated with equipment (compressors, drivers, vessels, exchangers and cold boxes); bulk commodities (pipes and valves) integral with a LNG Plant; and manufacturing and delivery (shipping) constraints. The cryogenic section of the LNG plant was the primary area of concern, particularly, the refrigeration compressors and drivers.

**Refrigeration Compressor-Driver Selection**

Selection of a driver for the large refrigeration compressors is one of the most critical aspects in the design of a LNG plant. The size of refrigeration compressor drivers has increased, as the LNG project owners focused on lowering LNG cost through economies-of-scale. As a result, the capacity of LNG plants has continued to grow with the movement of the industry from steam turbines to Frame 5 and 6 gas turbines to the Frame 7 gas turbines being installed today. So where is the technical limit?
Most recent LNG plants have utilized large single shaft gas turbines supplemented by electric starter/helper motors to drive the refrigerant compressors in the liquefaction process. For a given gas turbine, adding horsepower to the refrigeration compressor can be accomplished in a limited number of ways, such as: inlet air chilling of gas turbines or installation of larger helper motors.

The BGT compressor driver selection study began by evaluating the merits of industrial gas turbines, aero-derivative gas turbines, and large electric motors; however, it quickly became apparent that as traditional capacity limits were pushed, the compressors were also critical components that required significant review and understanding. As such, BP worked with Nuovo Pignone and Elliott to determine where the technical limits of the refrigeration compressor might be. The study showed that compressor sizes beyond 100MW were technically feasible, which means that utilization of a Frame 7E gas turbine with a 30-35 megawatt helper motor, a Frame 9 gas turbine plus a helper motor or a 100+ MW electric motor configuration are all possible. These large configurations move the LNG plant capacity to beyond 8 million tonnes per annum. There was some indication from the compressor vendors that the technical limit could be pushed out even further; however, this would require technology developments and the owner would have to assume additional technical risk.

The results of the study showed that increasing the helper motor size on the Frame 7 gas turbine driver could decrease the overall capital cost per annual tonne of LNG production ($/tpa) by approximately $0.9 per tpa per megawatt. For example, adding 30 MW to each of the refrigeration compressors, the $/tpa of LNG can be reduced by approximately $27/tpa. However, this has to be performed in conjunction with an optimization of the power generation for the LNG plant. Additionally, the CO₂ emissions per tonne of LNG can be reduced by about 0.5% per incremental MW of refrigeration horsepower. The study also showed that by utilizing a Frame 9 gas turbine as the refrigeration compressor driver, a slightly better reduction in capital cost per tonne of LNG produced could be achieved with about the same emissions improvement.

Beyond the Frame 9, utilization of large electric motors is seen as the only viable option to set the next benchmark in cost and emissions in the LNG industry. Based on the results of the BGT study, the All Electric plant design (eLNG) with large motors appears to have the best potential to meet the aggressive targets set for BP’s Next Generation LNG plant. Although General Electric does not offer a guarantee for the Frame 9 in mechanical drive service, we...
believe that in addition to moving toward large electric motors, the use of Frame 9’s for mechanical drive is the next logical step for the LNG industry.

**Rest of Plant**

For the large pieces of equipment, vessels and exchangers, transportation of the equipment appeared to be an issue, but not a technical limit. Certain suppliers with coastal facilities may be required since rail and highway transportation may be limited due to the component size.

As to the technical limit of the vessels and exchangers, vessel suppliers have welding and rolling capabilities up to 400 mm thickness with shop size limitations of 6 meter diameter and 30 meter tangent length plus crane capacities up to 1300 metric tonnes.

For the cold boxes and plate-fin heat exchangers, the size of the brazing furnace appeared to set the technical limit; however, this limit can be overcome by simply using multiple, smaller units to achieve the required duty.

The BGT study concluded that cryogenic piping components, in general, do not have a technical limit for pipe fabrication, welding or transportation. The shipping and installation costs for larger diameter piping significantly increase because smaller pipe, up to ~36-inch diameter, is shipped in double random lengths of up to 40 feet whereas larger pipe is fabricated in much shorter lengths, 6–10 feet; and the shorter pipe requires more field welding and hydrotesting. As illustrated by the cost curves for various stainless steel pipes, the technical limit for piping may in reality be a commercial or economic limit.

Every LNG plant includes a significant number of valves, both flanged and weld-end, in cryogenic service. As a general rule, the limit of cryogenic ball valves is 12-inch bore diameter and globe valve limits are 8-inch diameter. Butterfly valves are used for larger applications for economic reasons, not technical reasons. Cryogenic butterfly valve manufacturers have advised that they have the capability to fabricate cryogenic butterfly valves with a diameter of up to 80-inch. Valves of this size would be flanged; weld-end valves are limited to a maximum diameter of approximately 48-inches. As illustrated by the graph, the real technical limit is an economic limit.

**Optimization of Power Generation**

Historically, optimization of the power generation supply for LNG plants has not been a primary focus as the fuel gas was not valued and greenhouse gas emissions were not a
major concern. The primary focus has been on ensuring that the plant had an oversupply of electric power from low capital cost machines. This meant that the LNG plants had more, low efficiency gas turbine generator sets than were required, which would run at sub-optimal load factors. In the past, this approach had very little impact on the project economics, as the fuel gas was either free or nearly free. Additionally, the focus on greenhouse gas emissions was minimal at best. As new LNG projects are developed, the issues of fuel gas value and emissions have become more important to the host governments and the project promoters.

Optimization of power generation capacity to match the LNG plant power demand can provide substantial benefits without increasing the life cycle plant cost. In fact, we believe that life cycle cost can be decreased, overall plant efficiency can be improved, operating costs can be reduced and emissions lowered by simply optimizing the power generation design.

As an example, let’s suppose the LNG plant power demand is 100 MW, the fuel gas price is $1.00/mmbtu and the spare power generation sets are idle. To supply the 100MW, the options are 5 x Frame 5, 3 x Frame 6, 2 x Frame 7, 6 x LM2500, or 3 x LM6000 power generation sets. If the project focused on the lowest capital cost option, then Frame 5 would be selected as shown on the chart to the right.

However, if the project included fuel gas cost in the evaluation, then the LM6000 should be selected. Furthermore, the first year fuel gas savings is nearly equal to the capital cost difference as can be seen in the chart (below left). Had the spare power generation sets been used as spinning reserves, the fuel savings becomes even larger due to the inefficiency of the machines at lower load factors.

If the project’s focus was environmental or being Green, the most efficient power generation option would be selected, thus lowering the CO₂ emissions. As illustrated in the chart (above right), the LM6000 also provides the lowest CO₂ emissions of the options by more than 0.2 mmtpa of CO₂.
This means that the lowest life-cycle cost is not achieved with the lowest capital cost option, and that optimization of the power generation for the LNG plant can provide both economical and environmental benefits.

**Process Design Optimization**

Using the LIQUEFIN™ process as the basis for plant design, the BGT Project performed multiple process studies aimed at identifying opportunities to improve and/or optimize the overall plant design in three main areas:

- Increased plant capacity (mmtpa LNG production),
- Lower unit cost ($/tonne), and
- Reduced unit CO₂ emissions (tonne CO₂/tonne LNG).

A significant number of technology concepts evaluated by BGT, several were considered to have adequate merit to be carried forward as part of the three plant designs previously described. One particular study compared the relative effectiveness of allocating power to inlet compression, mixed refrigerant compression and end flash. The study concluded that the best use of additional power in the liquefaction plant was to add more power to the mixed refrigerant cycles; the second most efficient option was to add inlet compression.

Another study documented the benefits of liquid expanders in the LNG end-flash and in the High Pressure Mixed Refrigerant (MR2) circuit, respectively. The potential LNG production enhancement was estimated to be around 3.2 and 3.4%.

The LNG plant designs recommended for further study included the use of inlet compression and compression of the demethanizer overhead gas to 70 bar. These designs also utilize a gas turboexpander and liquid expanders on both the high pressure mixed refrigerant and the LNG end flash.

**Modular Systems LNG Plant Design Concept**

Increasing plant size and reducing costs has been a trend within the LNG industry that has allowed operators to capture economies-of-scale and drive liquefaction costs down. One of the major purposes of BGT was to attempt to identify whether limiting factors exist in this drive to increase plant size. However, a very large LNG plant results in challenges such as:
• How might the savings derived from economies of scale be captured within the constraints of a finite market for LNG?
• How likely is it that a market for LNG could be ramped up quickly enough to fill a very large plant of 5 to 8+ mmtpa?
• How might the plant capacity be matched to the development of the gas reserves required to fill a large LNG plant?
• Finally, how can the capital spending most closely match the development of reserves to maximize project return to the shareholders?

The Modular Systems LNG plant design may provide a solution to these challenges.

Historically, LNG plants have used the “train” concept, whereby an initial phase was built, followed by subsequent equivalent-sized expansions that look nearly identical to the first train. The proposed solution is a “Modular Systems” LNG plant design concept. Whereas a “train” expansion requires a virtual duplicate of the original plant, the modular systems plant is pre-built with expansion in mind. For example, utilizing the Modular Systems approach for the mole sieve dehydration system the configuration illustrated on the figure to the right could be envisaged.

One concept that has been embraced in the design of the eLNG plant utilizes a simple-cycle power plant to power the first production phase, followed by the installation of waste heat recovery equipment to provide power to the subsequent modular expansion phase. This results in a relatively inexpensive plant expansion with virtually no incremental greenhouse gas emissions. This represents a low-cost, low-emission modular plant that can grow to meet both supply and market demands as necessary, and this is accomplished with only minimal pre-investments.

The LIQUEFIN™ process uses two mixed refrigerants to precool and liquefy gas. The use of plate fin heat exchangers allows this heat exchange to take place inside of a relatively compact cold box. This feature allows plant expansion of nearly any size to be installed after the initial phase has been built, since the PFHE concept has no particular limits with respect to expandability. In conjunction with the power system expandable design, the liquefaction section and the refrigeration driver-compressors line-up could also be configured for expansion.

The capacities of future LNG plants will be limited largely by markets and commercial arrangements, and not by issues related to scale of equipment. Therefore, a Modular Systems plant design allows the LNG planner to address the ever-present conflicting project
goals (low cost LNG supply and plant capacity that meets market demand) in a very effective manner.

**LNG Process Benchmarking**

Historically, there have been efforts to benchmark the different LNG process technologies, but getting the plant designs on a rigorously equivalent basis has proven to be nearly impossible. This has been largely due to the fact that each technology had different operational sweet spots in their designs and optimal use of refrigeration horsepower was different for each LNG process. Consequently, each process had different plant capacities, process efficiencies and costs. By setting forth sufficient detailed design parameters and taking the optimization of the gas turbine drivers out of the process equation by substituting electric motors, BP believes that the BGT benchmarking exercise can be accomplished that will allow the different LNG process licensors to provide an optimized plant design that is on a satisfactorily equivalent basis.

**Conclusions**

The rapid improvement in unit costs and environmental performance of LNG plant, seen in recent years, is set to continue through further increase in scale, improved efficiency, new process and driver configurations, and plant optimization. BP’s BGT has adopted an open approach to technologies, some new to LNG, and shows how aggressive cost and environmental targets can be met. Application of BGT principles has the capability to set new benchmarks in the Industry.

Detailed study of limiting equipment shows that LNG plant capacity in excess of 8 million tonnes is feasible with acceptable technical risk, and that Frame 9 industrial gas turbines or large electric motors are the next step for compression drivers. Future plant size is likely to be determined by market, commercial or resource factors, rather than technical limits, and a modular systems approach may provide a flexible platform for meeting market needs and providing low-cost expansions.

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